

# **Processing and Preparation of Advanced Stirling Convertors for Extended Operation**

The U.S. Department of Energy (DOE), Lockheed Martin Space Company (LMSC), Sunpower Inc., and NASA Glenn Research Center (GRC) have been developing an Advanced Stirling Radioisotope Generator (ASRG) for use as a power system on space science missions. This generator will make use of the free-piston Stirling convertors to achieve higher conversion efficiency than currently available alternatives. NASA GRC is supporting the development of the ASRG by providing extended operation of several Sunpower Inc. Advanced Stirling Convertors (ASCs). In the past year and a half, eight ASCs have operated in continuous, unattended mode in both air and thermal vacuum environments. Hardware, software, and procedures were developed to prepare each convertor for extended operation with intended durations on the order of tens of thousands of hours. Steps taken to prepare a convertor for long-term operation included geometry measurements, thermocouple instrumentation, evaluation of working fluid purity, evacuation with bakeout, and high purity charge. Actions were also taken to ensure the reliability of support systems, such as data acquisition and automated shutdown checkouts. Once a convertor completed these steps, it underwent short-term testing to gather baseline performance data before initiating extended operation. These tests included insulation thermal loss characterization, low-temperature checkout, and full-temperature and power demonstration. This paper discusses the facilities developed to support continuous, unattended operation, and the processing results of the eight ASCs currently on test.

# Processing and Preparation of Advanced Stirling Convertors for Extended Operation

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# Advanced Stirling Convertors

Convertor Model	Heater Head Material	Hermetic	Hot-end Temperature, °C
ASC-1	MarM-247	N	850
ASC-0	Inconel 718	Y	650
ASC-1HS	MarM-247	Y	850

- ASC-1 Developed during Radioisotope Power Conversion Technology NRA contract, Phase II
- ASC-0 and ASC-1HS developed during expanded Phase II – included hermetic sealing task
- Predecessors to Advanced Stirling Radioisotope Generator units (ie ASC-E)



ASC-1



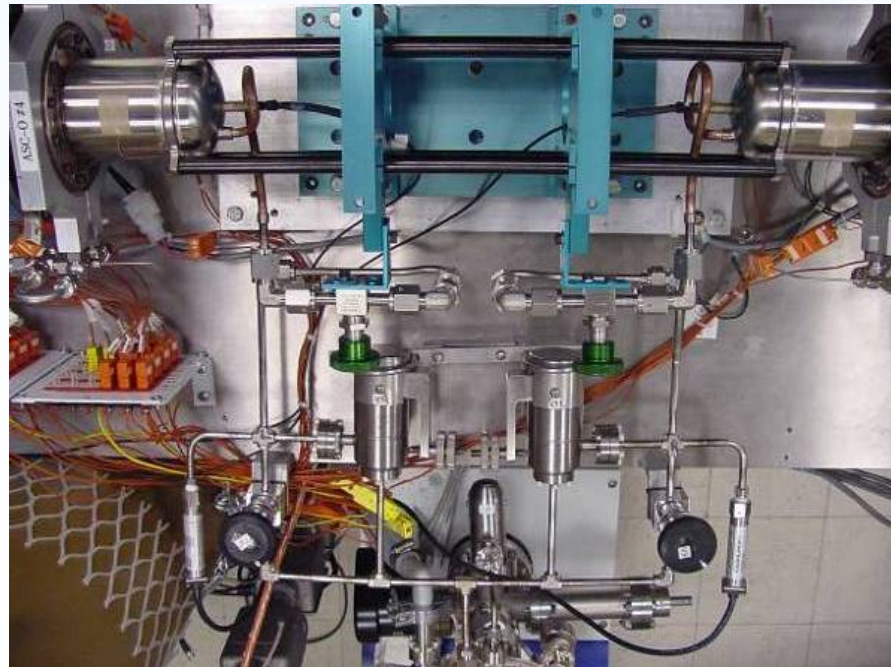
ASC-0



ASC-1HS

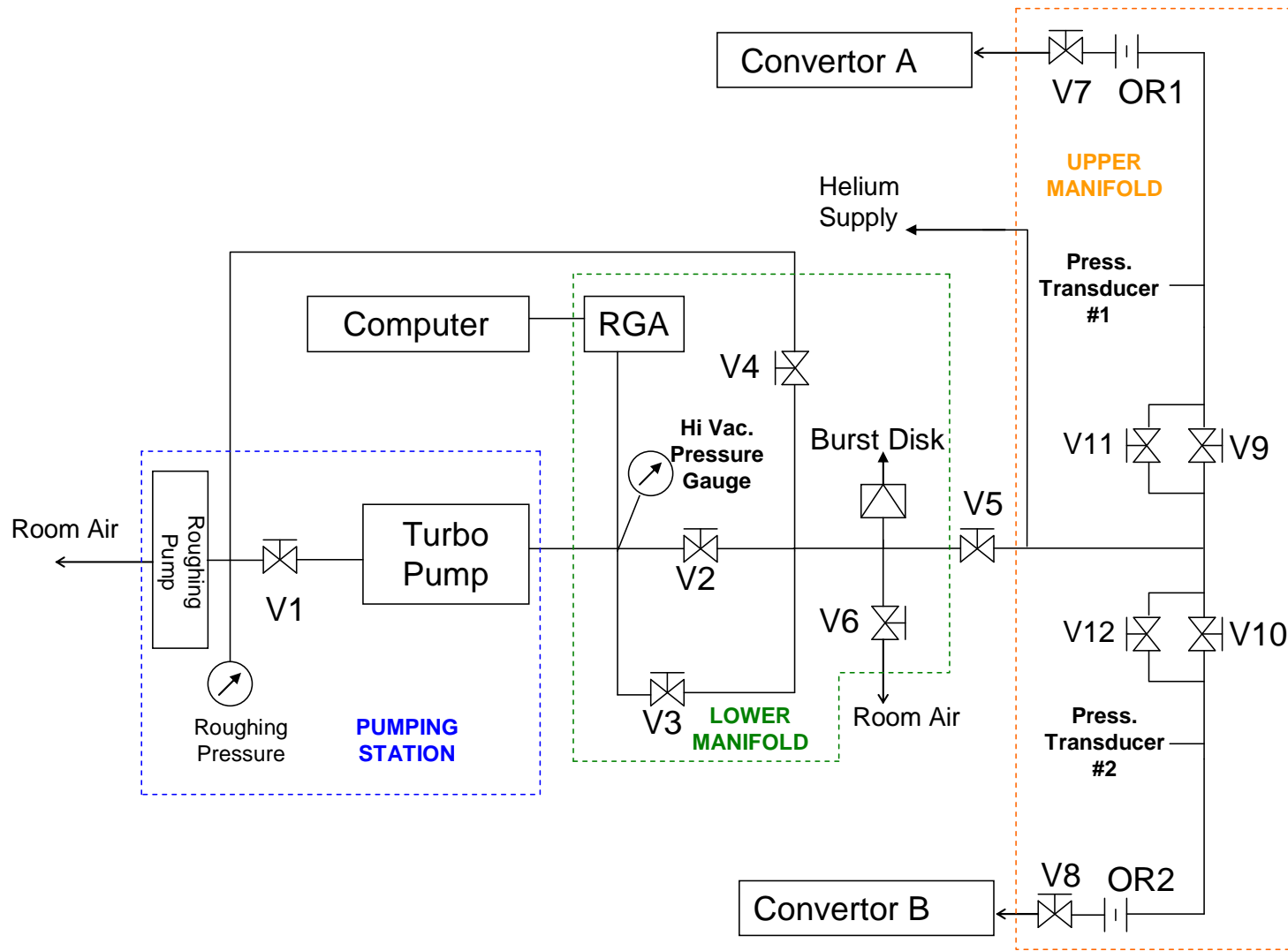
# ***NASA GRC Stirling Testing Capability***

- **Eight ASCs may be operated simultaneously**
  - 3 pairs in air
  - 1 pair in thermal vacuum
- **Gas management system**
  - Evacuation, bakeout and backfilling of convertors for ultra high purity charge
  - Charge pressure adjustment
  - Sampling and analysis of helium charge through residual gas analyzer



***Helium management system***

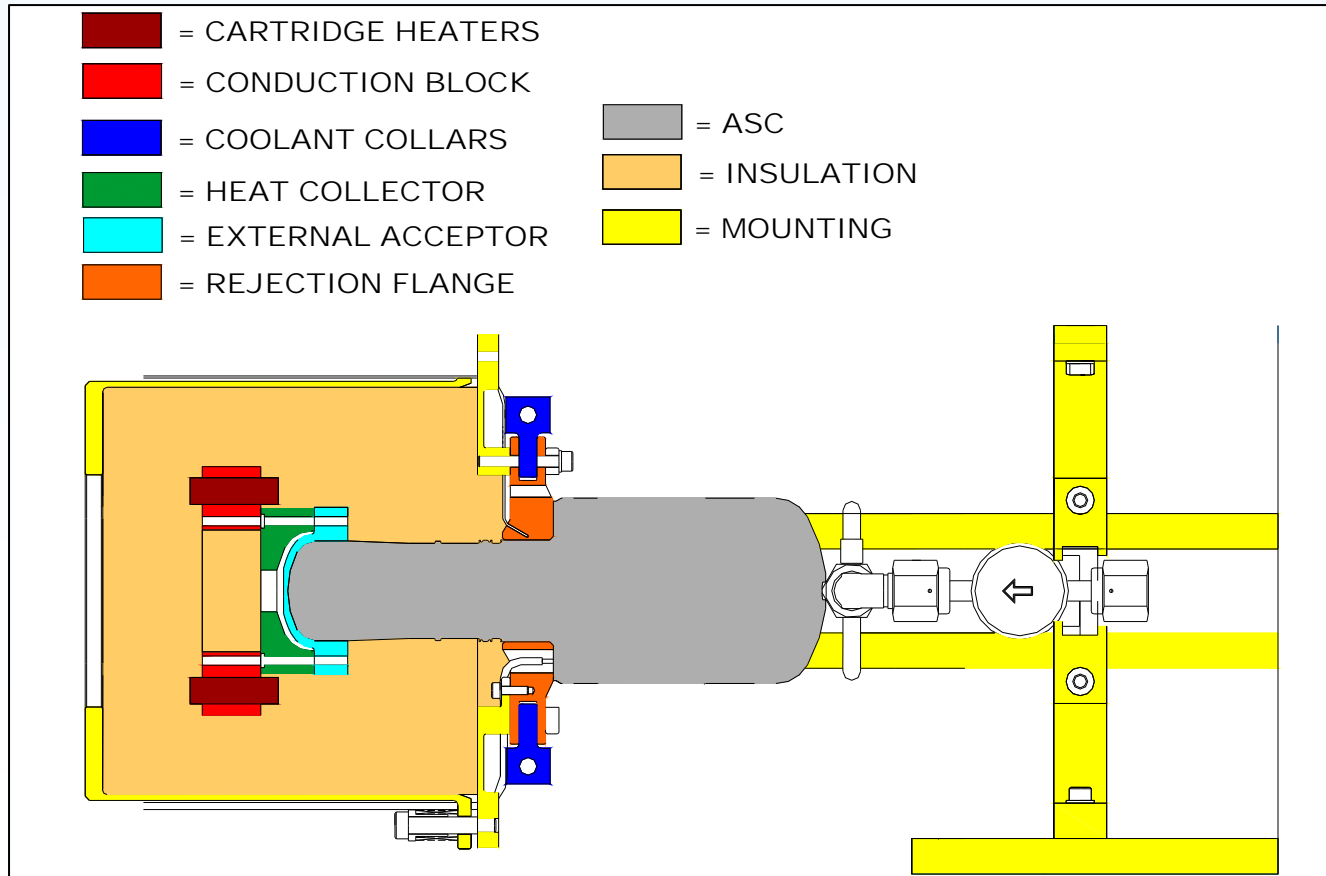
# NASA GRC Stirling Testing Capability



# Test Configuration

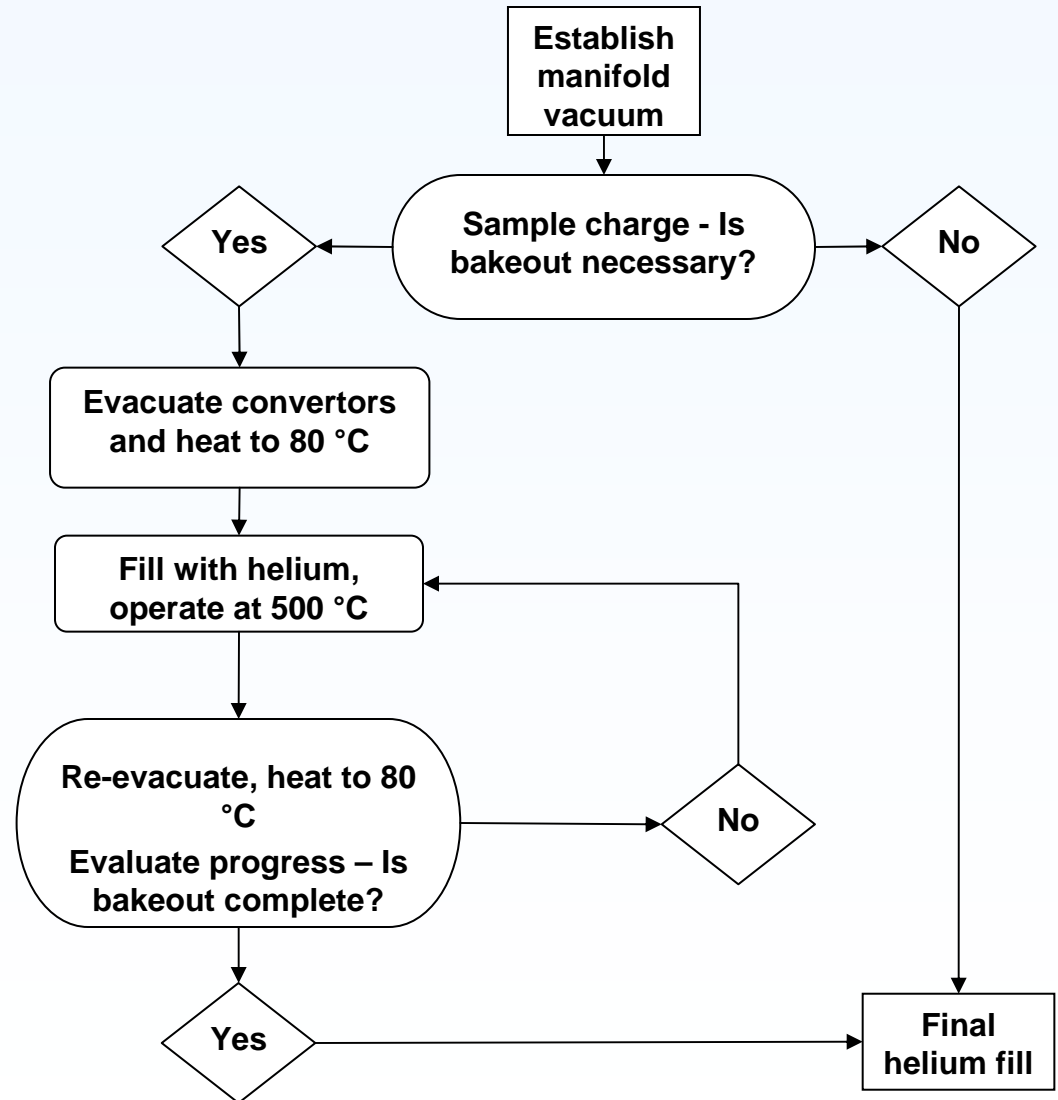
## In-Air

- Cartridge heater source
- Pumped-loop cooling
- Ceramic blanket hot-end insulation



# Revised Bakeout Procedure

- **Prior procedure consisted of only evacuation while heating**
  - Difficult to remove gas from behind seals or orifices (ie inside displacer)
- **Procedure revised to incorporate helium fill, operation, then re-evacuation**
  - Cycling of helium improves ability remove gas via laminar flow
  - Operation at 500 °C accelerates evolution of water
- **Progress evaluated each iteration at a defined state:**
  - Convertors being evacuated and heated to 80 °C
- **Procedure concluded by observing pressure vs. time plot**
- **RGA spectra recorded at room temp. before and after entire procedure to evaluate net effect**



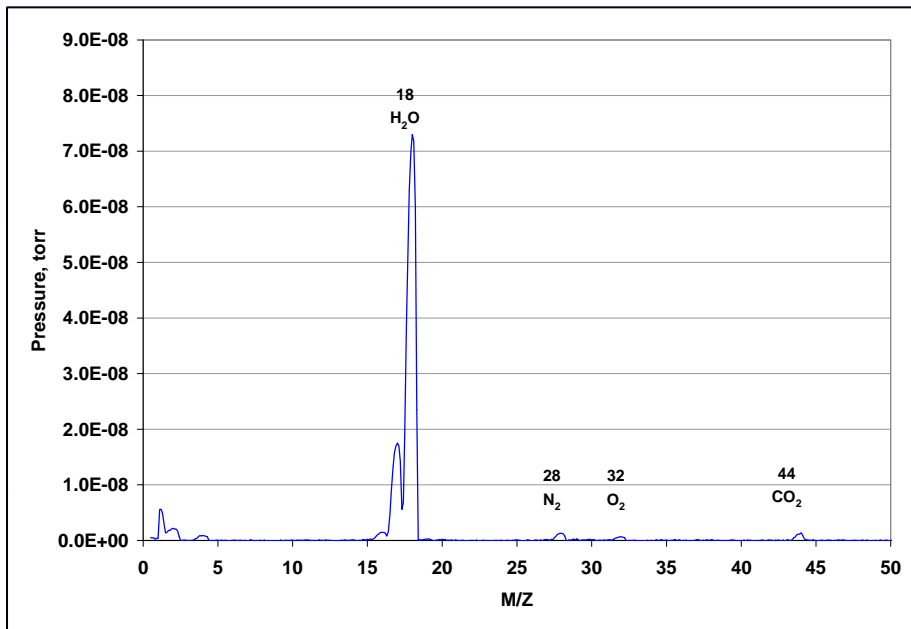
# Convertor Setup and Bakeout – ASC-0 #1 and #2

Total bakeout time = 4 days

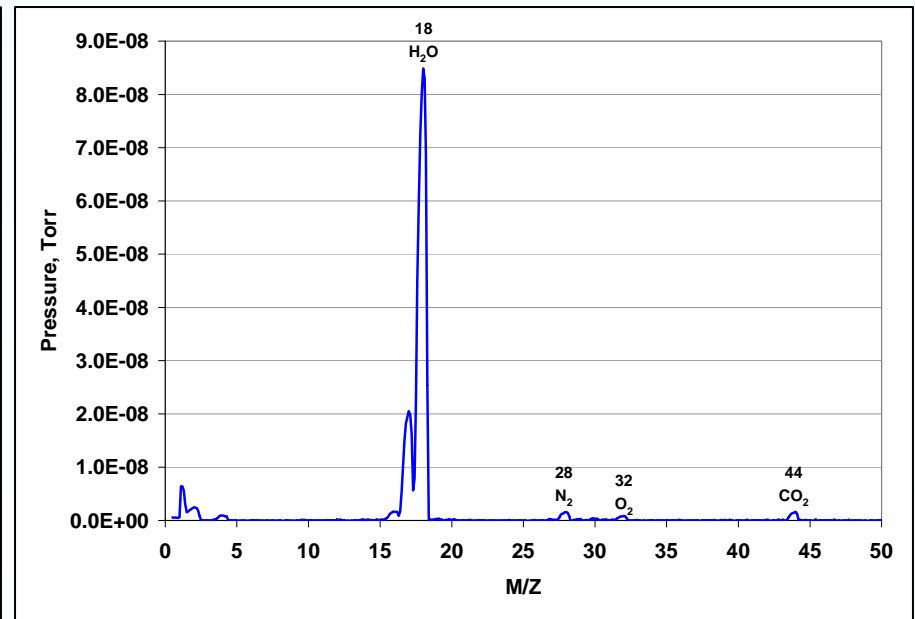
- Original procedure (no stages of operation)
- Heated to 70 °C for 9 hours
- Net effect: Total pressure reduced by > 2 decades

Initial Pressure =  $5.0 \times 10^{-5}$  torr

Final Pressure =  $3.1 \times 10^{-7}$  torr



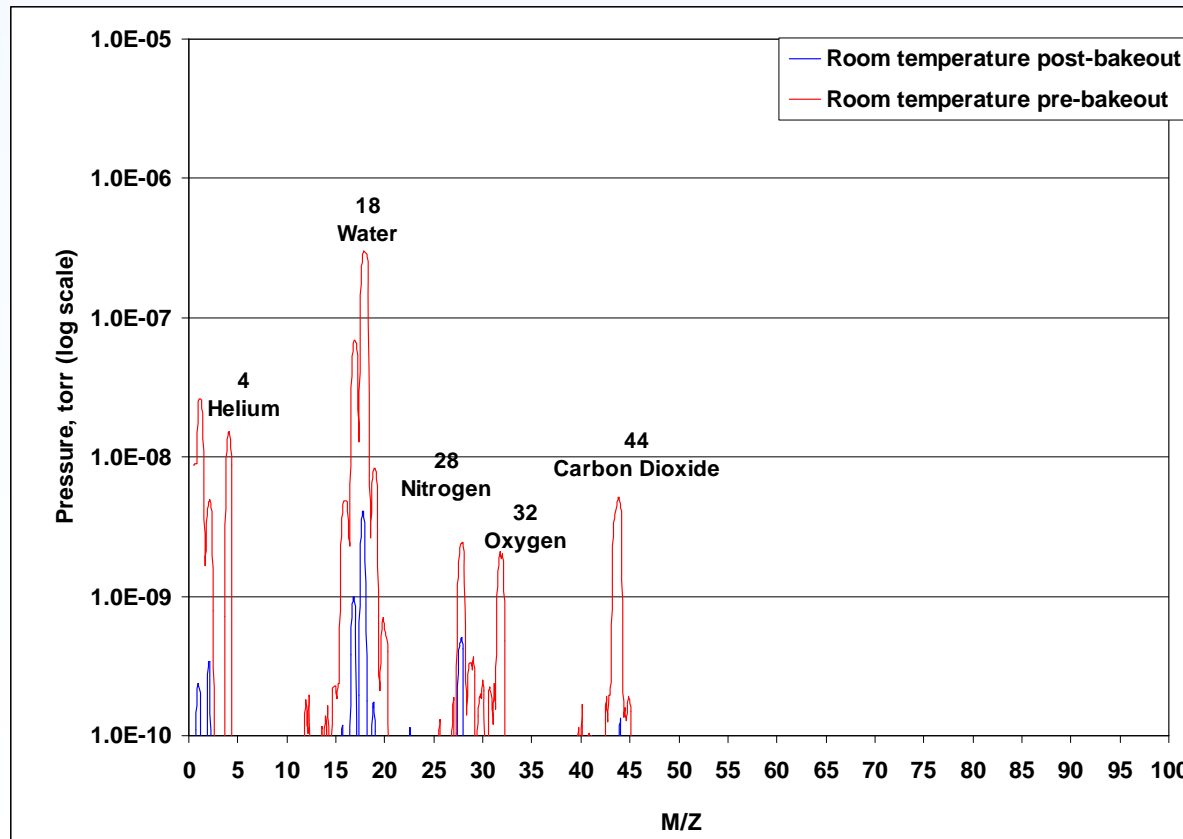
ASC-0 #1 post bakeout RGA spectrum



ASC-0 #2 post bakeout RGA spectrum

# Convertor Setup and Bakeout – ASC-0 #3 and #4

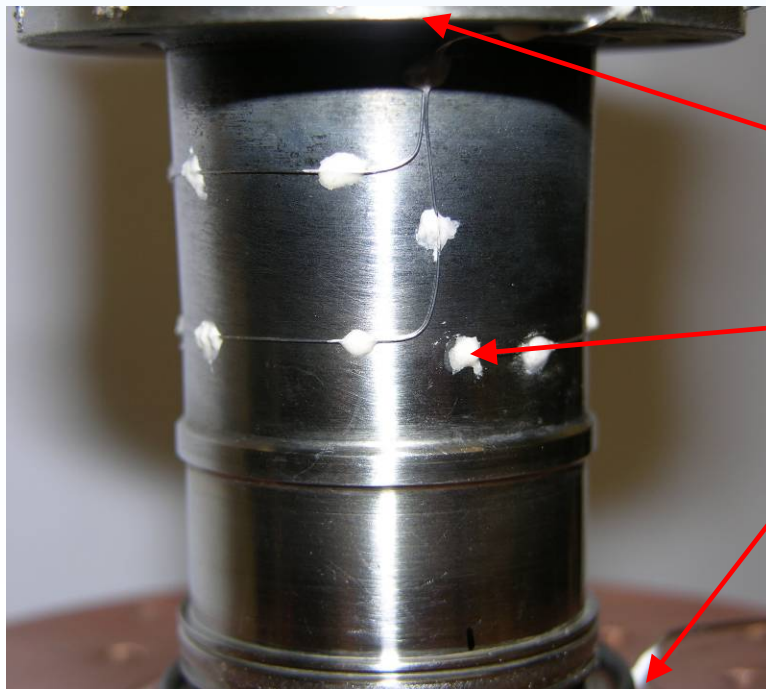
- Total bakeout time = 39 days
- Heated to 80 °C for majority of this time
- Three stages of operation at 500 °C hot-end (revised procedure)
- Insulation loss characterization completed concurrently
- Net effect: Total pressure reduced by approximately 2 decades



**Initial Pressure = 1.0e-6 torr**  
**Final Pressure = 3.3e-8 torr**

# Convertor Setup and Bakeout – ASC-1HS #1 and #2

- **Will be used for heater head structural model validation**
  - Heater head geometry mapped by laser measurement apparatus
- **Also used for heater head thermal model validation**
  - Thermocouples attached to heater head wall at three locations
  - Presented unique challenge due to small diameter (0.010”), and attachment method (high temperature ceramic adhesive)



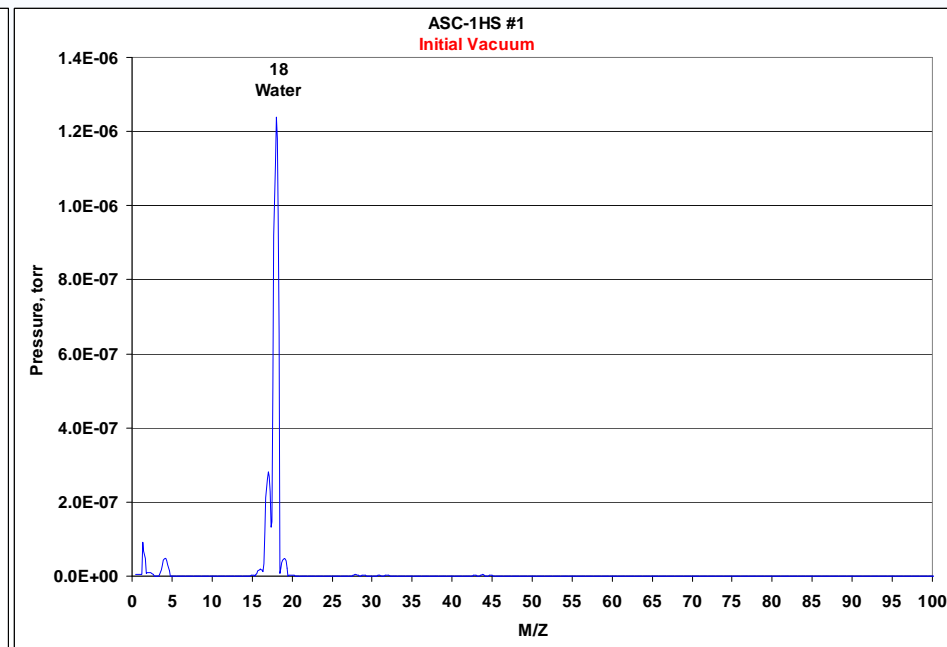
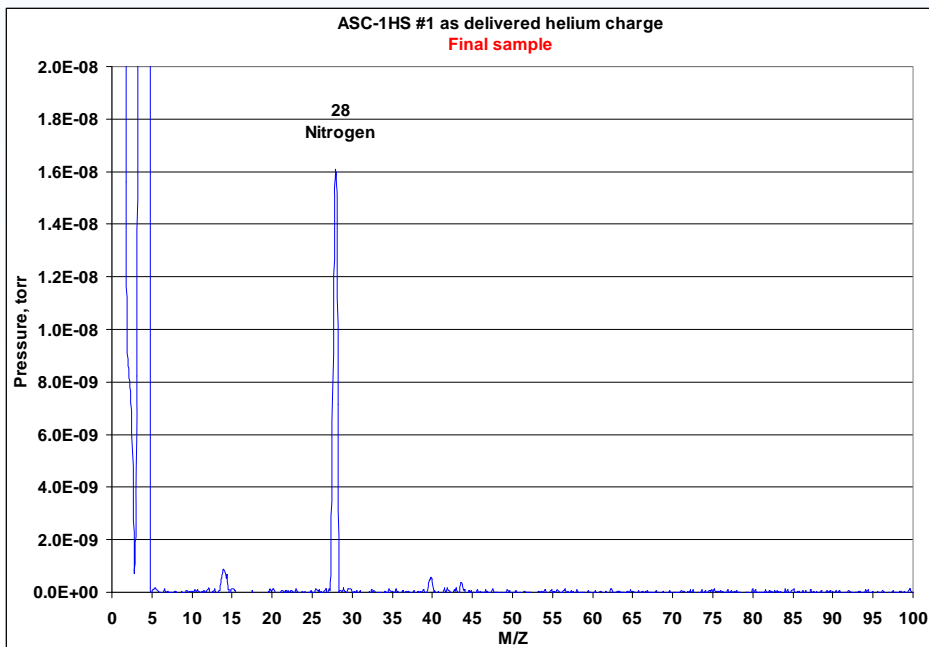
**Convertor hot end**

**Thermocouple Probe attached  
with ceramic adhesive**

**Convertor rejection end**

# Convertor Setup and Bakeout – ASC-1HS #1 and #2

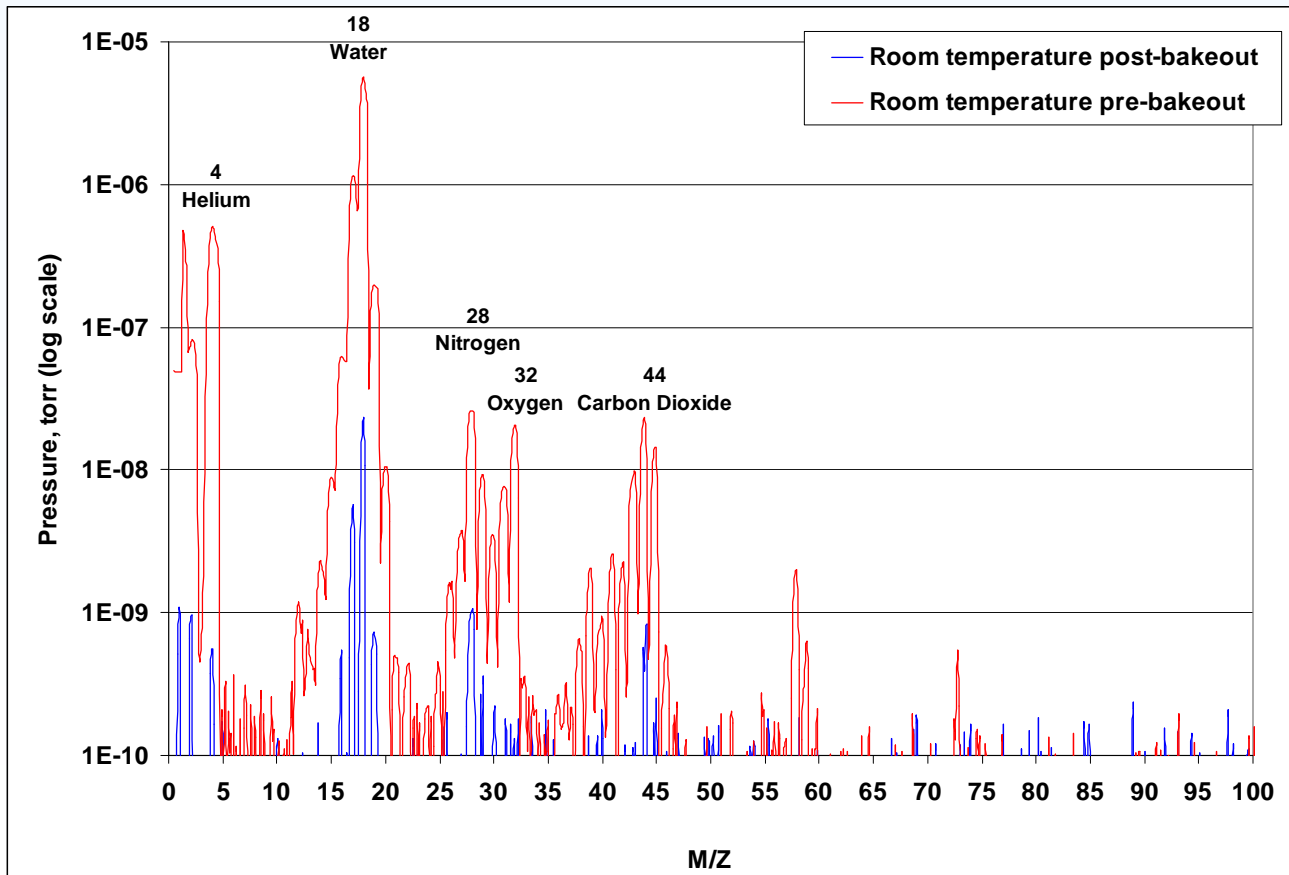
- Tested process to sample of as-delivered charge (evaluate necessity of bakeout)
- **Convertor #1 15 psig charge sampled**
  - Indicated no impurities other than nitrogen
  - Appeared very clean
- **Upon evacuation, large amount of water found present**
  - Higher than levels seen post bakeout of other convertors
  - Proceeded with bakeout



# Convertor Setup and Bakeout – ASC-1HS #1 and #2

Total bakeout time = 9.5 days

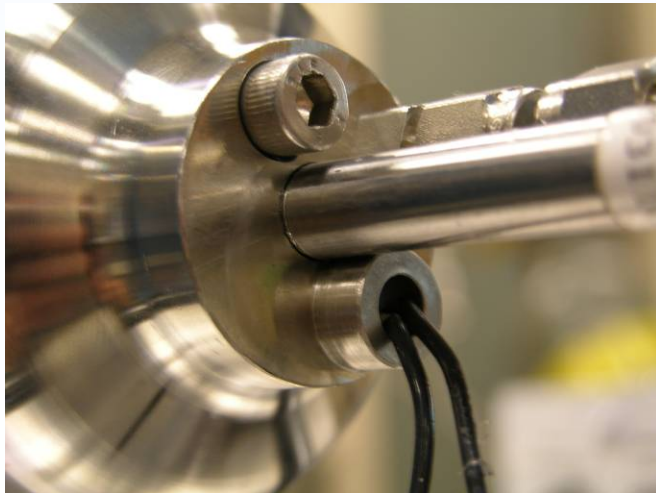
- Heated to 80 °C for majority of this time
- Three stages of operation at 500 °C hot-end
- Net effect: Total pressure reduced by nearly 3 decades



Initial Pressure = 1.9e-5 torr  
Final Pressure = 4.3e-8 torr

# Convertor Setup and Bakeout – ASC-1 #3 and #4

- **Total bakeout time = 5 days**
- **Heated to 75 °C for 5 days**
- **Net effect: Total pressure was not reduced**
  - Initial pressure =  $1.4 \times 10^{-5}$  torr
  - Final pressure =  $1.7 \times 10^{-5}$  torr
- **Outside environment was able to penetrate through o-ring seals easily enough to limit bakeout effectiveness**
  - 9 O-rings on each convertor for feedthroughs and seals
  - Designed for research; not extended operation



## ASC-1 pressure vessel aft end

- FLDT
- Helium port
- Alt feedthrough
- Spare port plug

# Baseline Testing

## Low-Temperature Checkout

- Initial operation at less-than-design hot-end temperature
- Conservative operating point to check functionality of new setup and convertor installation
- Maintained West temperature ratio when possible

$$W_T = \frac{T_H - T_C}{T_H + T_C}$$

$W_T$  = West temperature ratio  
 $T_H$  = Hot-end temperature, K  
 $T_C$  = Rejection temperature, K

## Full-Temperature Demonstration

- Operation at full design hot-end and rejection temperatures; demonstrates full design power output
- Other parameters adjusted to full design conditions (piston amp., charge press.,
- Data point used for comparison during extended operation

## Insulation Loss Characterization (Thermal)

- Convertors evacuated while measuring power input to maintain set of temperatures
- Plane fit correlation between temperatures and loss to environment through insulation
- Permits calculation of net efficiency



# Baseline Testing – ASC-0 #1 and #2

- **Low-temperature checkout : 548 °C hot-end, 50 °C rejection**
  - Rejection temp. limited by heat rejection hardware
- **Full-temperature demo : 650 °C hot-end, 90 °C rejection**

		Low-temperature checkout		Full-temperature demonstration	
Parameter	Units	ASC-0 #1	ASC-0 #2	ASC-0 #1	ASC-0 #2
Average Hot-end Temp.	°C	547.8	547.7	645.5	645.1
Rejection Temp.	°C	50.3	49.2	90.3	88.4
Net Efficiency	%	27.6	27.5	27.8	27.1
Alternator Power Output	W <sub>e</sub>	<b>64.7</b>	<b>63.7</b>	<b>68.9</b>	<b>64.8</b>
Operating Frequency	Hz	103.9	103.9	103.7	103.7

- **Insulation characterized at 550 °C and 650 °C**
- **79% insulation efficiency during full-temperature**

ASC-0 #1	
Hot-end temp. (T <sub>H</sub> ) °C	Insulation loss (Q <sub>loss</sub> ), W
550	47.5
650	66.3
ASC-0 #2	
Hot-end temp. (T <sub>H</sub> ) °C	Insulation loss (Q <sub>loss</sub> ), W
550	46.8
650	64.9

# Baseline Testing – ASC-0 #3 and #4

- **Low-temperature checkout** : 548 °C hot-end, 50 °C rejection
  - Rejection temp. limited by heat rejection hardware
- **Full-temperature demo** : 650 °C hot-end, 90 °C rejection

		Low-temperature checkout		Full-temperature demonstration	
Parameter	Units	ASC-0 #3	ASC-0 #4	ASC-0 #3	ASC-0 #4
Average Hot-end Temp.	°C	548.4	547.8	644.4	644.3
Rejection Temp.	°C	50.1	50.0	89.6	89.9
Net Efficiency	%	29.6	29.1	29.1	28.6
Alternator Power Output	W <sub>e</sub>	<b>72.2</b>	<b>72.0</b>	<b>75.1</b>	<b>74.9</b>
Operating Frequency	Hz	104.2	104.2	104.2	104.2

- **Insulation characterized at 550 °C and 650 °C**
- **80% insulation efficiency during full-temperature**

ASC-0 #3	
Hot-end temp. (T <sub>H</sub> ) °C	Insulation loss (Q <sub>loss</sub> ), W
550	47.6
650	66.0
ASC-0 #4	
Hot-end temp. (T <sub>H</sub> ) °C	Insulation loss (Q <sub>loss</sub> ), W
550	47.4
650	64.7

# Baseline Testing – ASC-1HS #1 and #2

- **Low-temperature checkout : 650 °C hot-end, 50 °C rejection**
  - Rejection temp. limited by heat rejection hardware, desired rejection temp. was 25 °C
- **Full-temperature demo : 850 °C hot-end, 90 °C rejection**

		Low-temperature checkout		Full-temperature demonstration	
Parameter	Units	ASC-1HS #1	ASC-1HS #2	ASC-1HS #1	ASC-1HS #2
Average Hot-end Temp.	°C	650.1	649.7	838.1	841.1
Rejection Temp.	°C	51.0	51.9	89.5	90.3
Gross Efficiency	%	24.3	24.0	22.8	23.1
Alternator Power Output	W <sub>e</sub>	<b>80.7</b>	<b>77.0</b>	<b>97.0</b>	<b>93.7</b>
Operating Frequency	Hz	102.0	102.0	102.0	102.0

- **No insulation loss characterization performed**
- **Net efficiency not available**



# Baseline Testing – ASC-1 #3 and #4

- **Low-temperature checkout : 650 °C hot-end, 25 °C rejection**
  - Directly coupled coolant loop enabled desired rejection temperature
- **Full-temperature demo : 850 °C hot-end, 90 °C rejection**

		Low-temperature checkout		Full-temperature demonstration	
Parameter	Units	ASC-1 #3	ASC-1 #4	ASC-1 #3	ASC-1 #4
Average Hot-end Temp.	°C	649.0	648.6	844.0	844.0
Rejection Temp.	°C	25.2	24.0	89.3	89.7
Gross Efficiency	%	21.9	21.2	17.9	18.9
Alternator Power Output	W <sub>e</sub>	68.2	64.7	71.0	56.8
Operating Frequency	Hz	103.1	103.1	103.0	103.0

- **Insulation characterized at 650 °C and 850 °C**
- **Conduction losses through high temperature heater head not yet developed**
- **Insulation package larger than ASC-0 design**
  - 17% less heater power required to maintain 650 °C



# Summary

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1. Eight convertors baked for clean helium fill
2. Revised bakeout procedure developed
3. Baseline convertor performance characterized at intermediate and full temperature conditions
4. Insulation thermal loss characterization performed on six convertors

